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Reversible Logic as a Strategy for Computing

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REVERSIBLE LOGIC AS A STRATEGY FOR COMPUTING

During the 1983 Summer Study, a few members of JASON attempted to survey the current status of the reversible logic approach to digital computing. Our aim was to form an opinion on which future developments of this subject might be relevant to DARPA's computer-related interests and possibly worthy of its support. We consulted one of the pioneers in this subject, Dr. Edward Fredkin of MIT, at some length and brought ourselves up to date on the (not very extensive) literature. Our basic conclusion is that the importance of reversible logic depends crucially on the physical architecture of the computer: It is irrelevant to the current scheme in which packets of charge are stored on, and moved between, structures of order one light wavelength in size, but might be relevant and even essential if the basic information-handling units were of molecular or atomic size (a distant but not necessarily unattainable goal). The question of physical realization of reversible logic elements has been almost completely neglected* in favor of the abstract questions of how, given the existence of reversible logic elements, one could wire them up to make a useful computer and how one would program it. We think that

*Apart from some interesting "existence proof" work of Fredkin et al.

- (K) 1

the problem of how to physically realize reversible computation at something like the atomic scale should be the next question to be attacked in this area. We also think that the very framework of reversible logic suggests some interesting new approaches to the problem of ultra-small-size computing elements which might be worth exploring for their own sake. Although practical payoff on any of these ideas is surely far off, the computer science and physics issues raised are fascinating and of fundamental importance.

Investigations in this area are probably deserving of DARPA support as topics in pure computer science. The body of this report amplifies these remarks.

Energy Dissipation in Computing

Contemporary computers dissipate at least 10^{-12} joules (about 10^8 kT, if T equals room temperature) per logical operation. The reason is that bits are stored as charges on capacitors charged to about one volt (the typical operating voltage of solid state electronic devices). Since there is a lower limit to the size and capacitance of circuit elements that can be fabricated on a chip using optical techniques, there is a lower limit to the energy associated with storing one bit. That limit turns out to be the above-mentioned 10^{12} joules, and the current style of computer logic causes that entire energy to be dissipated each time the state

of a bit is changed.¹ The resulting heat load is a major barrier to high speed computation.

A major question is the extent to which this dissipation is an inescapable concomitant of computation and to what extent it is due to "inefficient" physical or logical design of the computer.² Information theoretic/thermodynamic arguments have been used to suggest that there is a fundamental dissipation limit of kT per operation for computers designed on current principles.

In thermodynamics there is a well-known connection between dissipation and reversible operation of heat engines. Standard computer logic elements, the NAND gate in particular, are not even reversible as abstract logical operations, let alone as physical devices. It has been suggested that if reversible logic functions are used, it is, in principle, possible to do computing with zero dissipation!^{3,4} In this scenario, the entire computing operation would have to be carried out reversibly in analogy with the dissipationless operation of a reversible heat engine.

It is hard to evaluate the relative merits of two schemes which promise to reduce dissipation to $0 \cdot kT$ (the claimed limit for reversible logic) and $1 \cdot kT$ (the claimed limit for standard logic) per operation, respectively, when the best dissipation

achieved to date is 10^8 kT! We think it is worthwhile to pursue the reversible logic scenario, not so much because it promises superior practical benefits, but rather because it raises unfamiliar questions about the nature of computing and suggests some interesting new approaches to the physical realization of computation.

There are two types of questions which arise when you pursue this line. First, there are the questions of what are useful reversible logic functions, how might they be tied together to make a useful computer, and how might such a computer be programmed. These questions are all answerable in the abstract, without any reference to the physical realization of the system. This sort of question is the major subject of the work of Fredkin and other pioneers in reversible logic and the results are that manageable reversible logic computers can be designed, although they are in many interesting ways different from conventional computers. The second question has to do with physical realization of reversible computation. What sort of physical system can be used, what calculation speeds can be achieved, etc.? Here very little is known, although many interesting questions arise. We think this is the most important aspect of the reversible computation problem and have attempted to construct a framework for a serious exploration of these questions.

Physical Realizations of Computers

To establish a useful framework for our discussion, it is helpful to remark that there are at least two broad classes of physical realizations of computing machines. The most important distinction is between open (dissipative) systems and closed (conservative) systems. The distinction is between systems in which the computational degrees of freedom are coupled to a "heat bath" with which energy can be exchanged and systems in which the computational degrees of freedom are effectively isolated from the rest of the world. The other essential distinction is between systems in which the computational degrees of freedom can be described classically versus those in which they must be described quantum mechanically.

A dissipative system will behave in many respects like a heat engine. In particular, it should be possible to design it so that it is more and more reversible and less and less dissipative the slower it runs. This suggests an interesting tradeoff between dissipation and speed of operation, about which we will be more quantitative in the next section. (The logical architecture of such a machine could be either reversible or not.)

A conservative system is necessarily reversible because any closed Hamiltonian system is reversible. In fact, it is physically

reversible whatever its speed of operation, and it would hardly make sense for the logical architecture of such a machine to be anything other than reversible!

Any device in which the computational degrees of freedom are realized on a scale much larger than atomic size will inevitably be dissipative: the total number of physical degrees of freedom vastly outnumber those directly involved in computation, and it is impossible to prevent leakage of energy between the computer and the "heat bath." This is the case with all present-day machines.

On the other hand, if the computational system were realized at the atomic scale, as some kind of cleverly constructed lattice, for instance, then the computational degrees of freedom would be a major fraction of the total number of degrees of freedom. In that case, the system might function as a good approximation to a closed reversible Hamiltonian system, and the choice of reversible logic structure would be essential. Needless to say, no one has any practical ideas on how to realize such a computing system, though, of course, the entire thrust of the development of faster computation is toward physically smaller computing elements. The point is that if atomic scale computing elements are ever constructed, reversible logic ideas may be most appropriate to doing computation with them.

The other important dichotomy in thinking about physical realizations of computers is that between classical and quantum mechanical systems. This leads to a two-by-two classification scheme which is shown in Fig. 1.

		Open	Closed
		Conventional Machines	Fredkin's Billiard Ball Machine
		Josephson Junction	Future Atomic Scale Machines?
Classical		Macroscopic	Microscopic
Quantum Mechanical			

Figure 1

Current computers are macroscopic and therefore classical and dissipative. Computers constructed at the atomic scale are surely quantum-mechanical and might well, for the reasons discussed earlier, be effectively closed reversible systems.

Non-dissipative classical systems are consistent with Newtonian mechanics and represent internally consistent idealized systems which turn out to be a useful framework for demonstrating general features of reversible computation. We will be discussing Fredkin's billiard ball model in that light. Finally, there exist macroscopic (i.e., dissipative) but quantum-mechanical logic devices based on the Josephson junction which we will use to illustrate more precisely the theoretical limits on dissipative devices.

Theoretical Limits for Dissipative Devices

The single junction superconducting interferometer provides an example of a dissipative logic device whose properties can be quantitatively analyzed in some detail. In this section, we summarize the results of Likharev⁵ on the device schematized in Fig. 2.

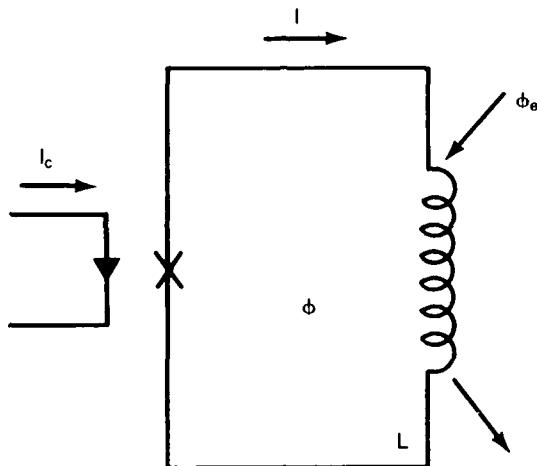


Figure 2

It consists of a superconducting ring, broken by a Josephson junction (the cross in the figure), with provision for controlling the maximum current, I_M , that can flow through the junction by varying an external current, I_c . The superconducting ring is subject to an external magnetic field with a flux, ϕ_e , through the ring. The ring carries a current, I , and has a net flux, ϕ , due to the combined effects of I and ϕ_e through it. If the self-inductance of the ring is L , the net flux satisfies

$$\phi = \phi_e - LI$$

The net flux, ϕ , is proportional to δ , the difference of the superconducting order parameter phase across the junction and can be thought of as the variable describing the "state" of this system.

To be precise, $\delta = 2\pi\phi/\phi_0$, where $\phi_0 = \frac{\hbar}{2e}$ is the magnetic flux quantum. The system is made to function as a logic device by manipulating the state variable through changes in the external parameters I_c and ϕ_e .

The energy of this system is the sum of the magnetic field energy

$$U_M = \frac{1}{2} LI^2 = \frac{1}{2L} (\phi - \phi_e)^2$$

and the energy of a junction with a phase difference δ across it

$$U_J = + I_M \frac{\phi_0}{2\pi} \cos \delta$$

$$= I_M \phi_0 / 2\pi \cos (2\pi\phi/\phi_0) .$$

(I_M is the maximum junction current which, as we have said, can be manipulated from the outside.) The total energy functional,

$$U(\phi) = \frac{1}{2L} (\phi - \phi_e)^2 + \frac{I_M \phi_0}{2\pi} \cos \frac{2\pi\phi}{\phi_0}$$

generically has two minima. The situation when $\phi_e = 0$ and $I_M > 0$ is shown in Fig. 3.

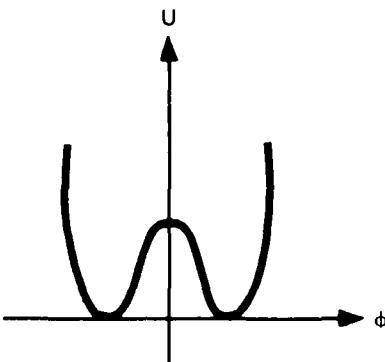


Figure 3

This two-fold degeneracy of the lowest-energy state can, in principle, be used to store one binary bit of information.

Better yet, we can, by changing the external parameters, I_M and ϕ_e , manipulate the shape of the potential in such a way as to smoothly switch the system point from one degenerate ground-state to the other. This gives an explicit way of switching our bit-storage device or carrying out an elementary logical operation. A possible switching sequence is shown in Fig. 4, where the system point (the heavy dot) starts in the right-hand well and finishes in the left-hand well.

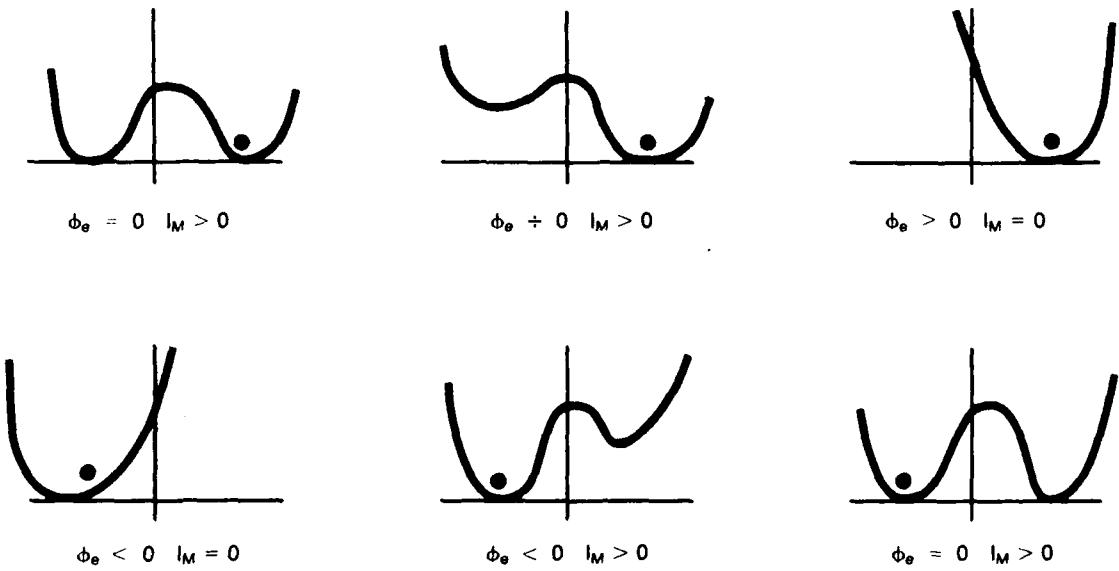


Figure 4

In this sequence, the system point always sits at a local potential minimum and the rate of change of the system coordinate is always completely controlled by the external parameters and can be made as small as we like at the price of dragging the switching event out over a longer and longer time. In Fig. 5 we display a switching sequence where this is not true.

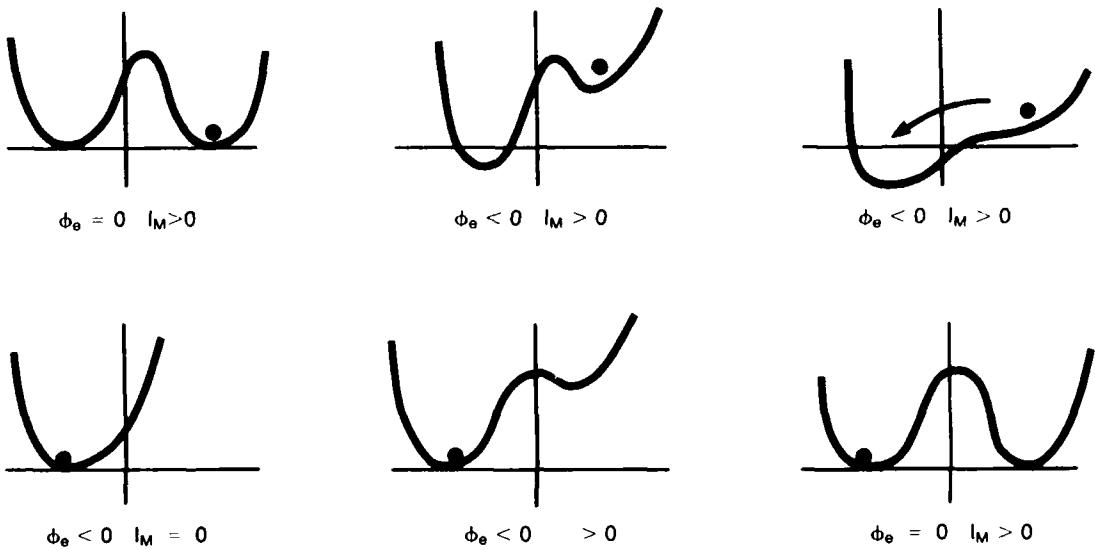


Figure 5

In the third step of this sequence, when the barrier finally disappears, the system point is at a large positive energy with respect to the left hand minimum. It will roll down the hill and eventually settle down in the left-hand minimum only after dissipating its extra energy. The rate of this motion and the energy dissipated in it are not controllable from the outside, and to minimize dissipation in switching we must avoid this sort of sequence.

We finally come to the quantitative evaluation of dissipation in the switching event. This device has many more

coordinates than the single flux coordinate, ϕ , in which we are primarily interested. The effect of these degrees of freedom can be summarized by a viscous force

$$F_v = -K \dot{\phi}$$

which leads to damping of motions of the system coordinate (and dissipation of energy from the ϕ degree of freedom) at a rate determined by K . The total energy loss in some time evolution of ϕ is just

$$W = - \int dt F_v \dot{\phi} = +K \int dt \dot{\phi}^2 > 0 .$$

It is particularly convenient to characterise the damping by the time, τ_c , it takes small amplitude oscillations about a minimum to decay by e^{-1} . In either of the switching scenarios described above, $\dot{\phi}$ necessarily is non-zero and there is necessarily some dissipation. The shape of the potential during the switching event is constrained by the requirement that spontaneous switching into the wrong well due to classical thermal fluctuations must be negligible (this means that the energy barrier between the two local minima must always be much greater than kT).

Given this information, it is a straightforward matter to calculate the minimum energy dissipation (corresponding to the sequence of Fig. 4) in a switching event carried out in a time interval τ . The result is, roughly,

$$W \sim kT \cdot \frac{\tau_c}{\tau}$$

so long as $\tau \gtrsim \tau_c$. In other words, the total energy dissipated in a switching cycle can be made as small as we like by making the switching time arbitrarily long compared to the basic dissipation time scale. This is analogous to the situation with heat engines: dissipation or entropy production can be made arbitrarily small by running the engine arbitrarily slowly. We can also determine the energy dissipated in a switching cycle like that of Fig. 5. In that case it turns out that

$$W \gtrsim kT$$

no matter how slowly we carry out the transition (at some stage the system executes free fall down a potential hill whose height is scaled by kT so that the system must dissipate energy of order kT to come into equilibrium).

When this sort of device is used to make a computer, the question of overall logical organization inevitably arises. It turns out that if we use the conventional organization based on (logically irreversible) NAND gates (which can be simulated by appropriately connecting together several of the above-described switches), then switching cycles of the type of Fig. 5 are inescapable and dissipation at the rate of roughly kT per operation is the theoretical limit. However, if a logically reversible organization is used, it turns out that only switching sequences of the type of Fig. 4 need be encountered and the dissipation per operation can be reduced arbitrarily below kT , at the price of reducing the rate of computation. Since the motivation for reducing dissipation was to increase the rate of computation, this seems rather self-defeating. Later on we will discuss possibilities in which, at least in principle, dissipationless reversible computation can be carried out at arbitrary speed. In the next section we will finally make explicit what we mean by reversible logical architecture and devices.

Reversible Computation-Abstract Issues

It is a commonplace of computer science that a computer can be built entirely out of a Boolean logic device called a NAND gate. The action of such a device is symbolized in Fig 6.

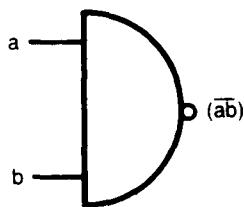


Figure 6

The inputs a and b take on the values 0 or 1 as does the output. The output is computed by the function (\bar{ab}) where the bar means logical "not" ($U = 1$, $T = 0$). This logical function is clearly not reversible or invertible since several input states produce the same output state. For this reason, a conventional computer cannot be run backwards. The previous section implies that the operation of a physical NAND gate entails a dissipation of at least kT per operation.

The discussion of the logical organization of strictly reversible computers was initiated by Bennett some ten years ago.³ In pursuing this subject, Fredkin developed a simple abstract reversible logical function which gave promise of being a universal

building block for reversible computers.⁴ The structure and action of this function, called the Fredkin gate, is shown in Fig. 7.

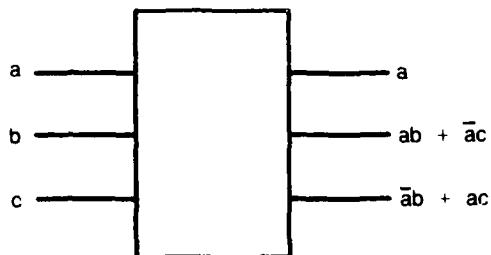


Figure 7

As in the case of the NAND gates, the input and output lines take on the values 0 or 1. An examination of the truth table for this device shows that it is invertible: the correspondence between input and output states is one-to-one.

By ignoring some outputs and fixing some inputs, the Fredkin gate can be made to perform any standard logical function. For instance, the AND of a, b can be obtained by setting $c = 0$ and keeping only the middle output line, as in Fig. 8.



Figure 8

This procedure requires a supply of input constants and a way of disposing of the unwanted outputs, known as "garbage." The brute force method of carrying out reversible computation is to record every one of the garbage constants which is produced during a computation. This is not a very satisfactory proceeding since the number of elementary logical operations required to carry out even a simple arithmetic operation, let alone a complicated program, is enormous and memory resources would be swamped.

Fredkin, Toffoli, and students have shown how to get round this problem by really making use of the reversibility of the system.^{6,7} The point is that if one is doing some machine instruction such as computing the sum of two numbers which involves a large number of logical operations, one may a) do the calculation,

producing a large quantity of garbage; b) record the result, producing a very small amount of garbage; c) run the computation backwards, eating up the garbage produced in a). If the machine instruction itself is logically reversible, as in

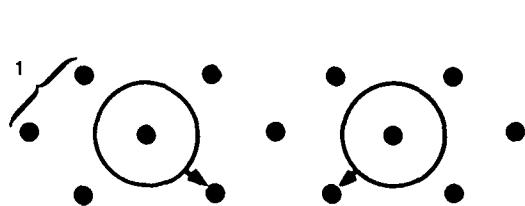
$(A, B) \rightarrow \left(\frac{A+B}{2}, \frac{A-B}{2}\right)$, one doesn't even have to accumulate garbage in step b). The only true garbage which needs special memory allocation and has to be kept to the end of the program is that associated with truly non-invertible machine instructions. By careful design of the machine instruction set and programming practices, it appears possible to reduce the garbage accumulated in a typical program to a manageable size. We are not aware of a quantitative answer to the question, if a program requires a total of N steps to execute, what is the minimum number of garbage bits that must be accumulated? We suspect that the answer is $\log N$, which would mean that only a trivial amount of memory has to be devoted to true garbage accumulation, but we don't have a proof.

Finally, as a result of this experience, Fredkin and students have been able to produce sketchy but credible designs for real computers. These designs are explicit two-dimensional wiring diagram layouts of Fredkin gates, and have been demonstrated in computer simulation exercises to work as expected.

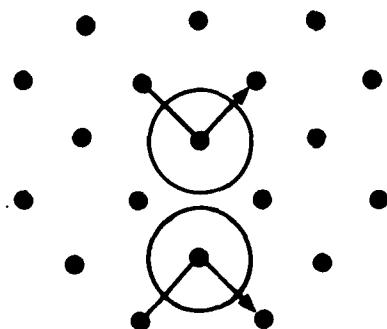
To summarize, although computers based on reversible logic elements have some unfamiliar features, machines whose effective operation is nearly a carbon copy of conventional computers can be laid out as explicit two-dimensional hookups of the logically reversible Fredkin gate. In the next section we will take up the question whether the Fredkin gate is physically realizable.

Physical Realization of the Fredkin Gate

In order to give an existence proof for reversible computation, Fredkin has introduced a stylized model based on perfectly elastic collisions of billiard balls moving on a frictionless plane.⁴ Consider a two-dimensional square grid as laid out in Fig. 9a, with unit spacing between the grid points and with identical hard spheres of radius $1/\sqrt{2}$ moving at one lattice spacing per time step along the principal directions of this lattice (again, as shown in Fig. 9a). At time $t = 0$, the center of every ball lies on a grid point and that will again be true at every integer-valued time. Balls will occasionally undergo right-angle elastic collisions at integer-valued times (Fig. 9b).



9a



9b

Figure 9a,b

The balls emerging from the collision will again move along the principal lattice directions and their centers will coincide with lattice points at integer-valued times. At some lattice points a billiard ball will be nailed down to function as a perfect reflector of anything that comes by. The presence or absence of a billiard ball at a lattice site at an integer time can be taken as a binary bit of information and the Newtonian evolution of such a system of billiard balls amounts to a "calculation" involving those bits.

The construction of the billiard ball realization of the Fredkin gate goes in two steps. First, construct the gate shown in Fig. 10 (called the interaction gate) where the bar represents a fixed reflector.

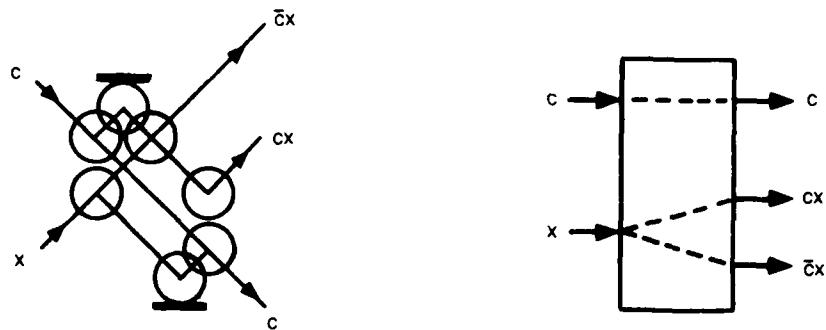


Figure 10

This device lets a ball on the x path go through undeflected if no ball is on the c path, but switches it onto a different path if a ball is simultaneously present on the c path (and lets the c ball through undeflected). The information processing here amounts to switching bits between two output paths, depending on the content of a control path. If these interaction gates are strung together according to Fig. 10 (where the connecting paths have appropriate delays in them to maintain proper synchronization), it is possible to verify that the overall system functions exactly like the Fredkin gate.

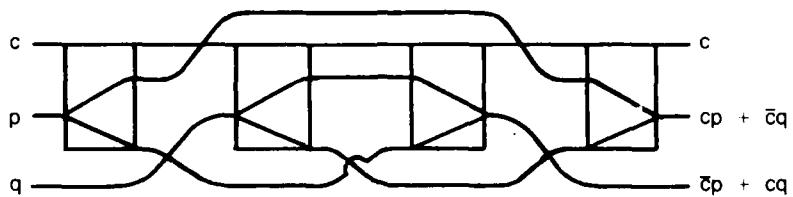


Figure 11

According to the previous section, a useful reversible computer can be made by wiring together enough Fredkin gates. The same computer can therefore be realized as a two-dimensional arrangement of appropriately aimed and placed billiard balls and reflectors. The execution of a program on such a computer is just the carrying out of the Newtonian time evolution of the mechanical system.

By construction, this system is dissipation-free and, since the billiard ball velocity is arbitrary, it can operate at any speed we like. This amounts to an existence proof for dissipation-free fast computing via a classical conservative system.

Billiard Ball Machine as Cellular Automaton

The defects of the billiard ball model as a practical physical realization of reversible computing are fairly obvious. It does, however, have the virtue of suggesting a different abstract framework within which some interesting new possibilities for physical realization suggest themselves.

The essence of the billiard ball model is that at integer time steps billiard balls are located at lattice points only and the pattern of occupied lattice sites changes from one time step to the next according to some rule. The rule is not made explicit, but is the result of evolving the previous configuration according to Newtonian mechanics. The step by step evolution of the state of a lattice according to a local rule is the subject of cellular automaton theory, a particularly active branch of fundamental computer science. It is natural to ask whether the essence of the billiard ball model can be captured in some cellular automaton rule. For the moment, this is just an idle question, but in the next section we will see that the cellular automaton framework is one into which it might be possible to fit real atomic physics.

There is indeed a cellular automaton version of the billiard ball machine which we have reconstructed from remarks of

Fredkin. Consider a lattice divided up into individual cells by solid and dotted lines in the manner of Fig. 12.

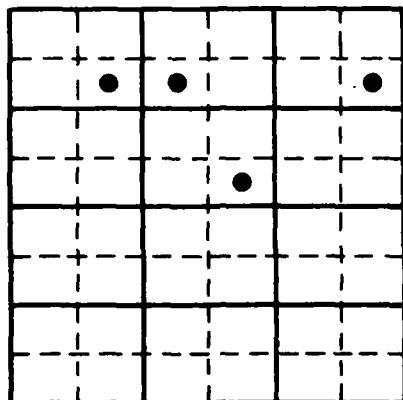


Figure 12

Some of the cells are occupied, and we want to devise a transition rule to cause the pattern of occupation to change. If we look at the unit cells defined by the solid lines alone or the dotted lines alone, we see that they each contain four of the unit cells of the full lattice. The transition rule will be defined for such groups of four cells and applied on alternate time steps to the groups defined by the solid lines and dotted lines. The transition rules we will use are defined in Fig. 13.

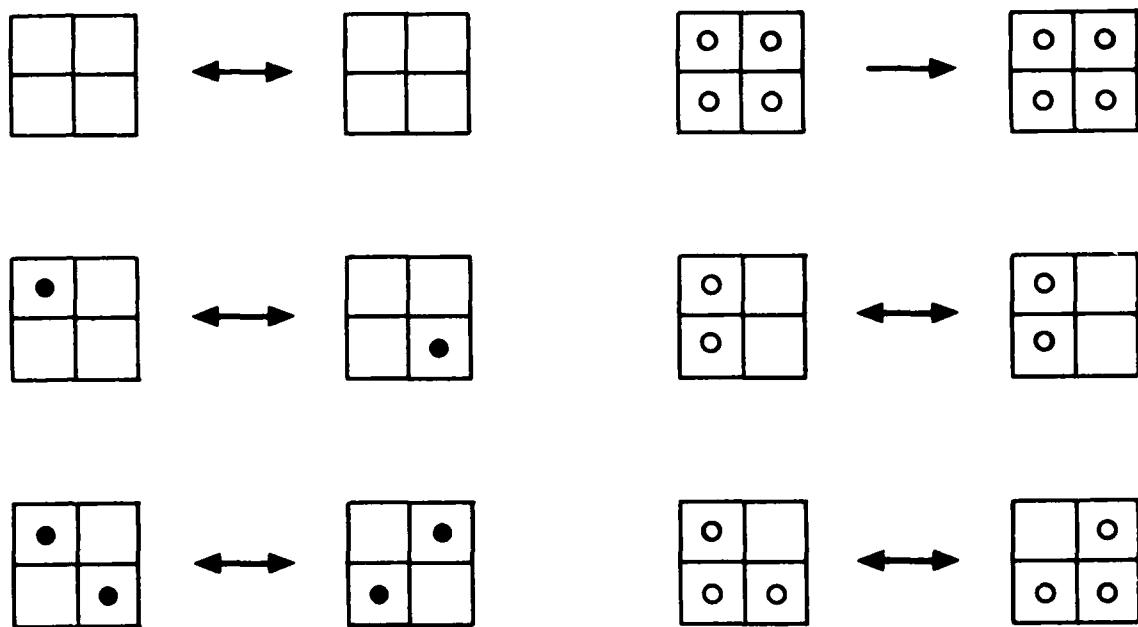


Figure 13

Rotations of the rules presented are also valid. The transformation effected by these rules is obviously one-to-one within the group of four cells on which they act. By extension, the action of these rules on the lattice as a whole is one-to-one and reversible.

A bit of playing with the rules shows that single occupied cells propagate like billiard balls in the manner indicated in Fig. 14.

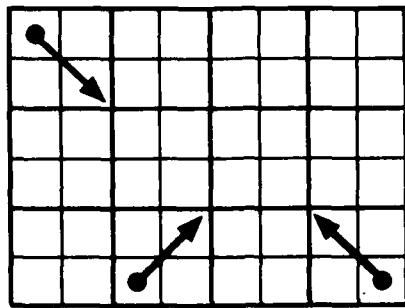


Figure 14

Single occupied cells, however, do not collide with each other in the manner of billiard balls. In order for this to work out properly, it is necessary to consider a train of two similar occupied cells, as Fig. 15.

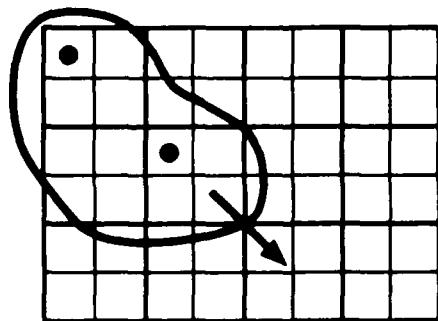


Figure 15

This, and the three other versions corresponding to the other possible directions of motion propagate and collide exactly in the manner of billiard balls. One can also construct a configuration which does not propagate and reflects any billiard ball configuration incident on it (see Fig. 16).

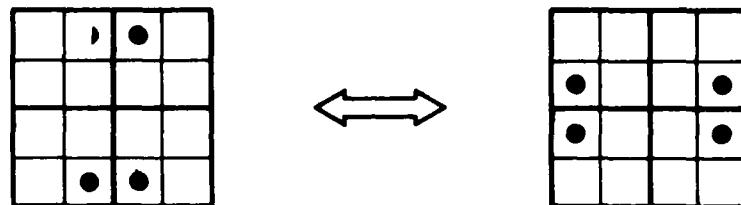


Figure 16

As the previous sections have shown, an explicit reversible computer design is available once we have "billiard balls" and "mirrors." Now that we know that our cellular automaton rules produce these two types of object, it is possible, in a perfectly explicit way, to construct a reversible cellular automaton computer. This is interesting because, as we shall argue in the next section, the cellular automaton framework seems particularly well-suited to realization at the atomic lattice scale.

Notional Atomic Scale Realizations

We have argued that reversible computing ideas are likely to be of most interest in the study of computers realized at the atomic scale, where the computational degrees of freedom are not vastly outnumbered by all the rest and a computer might function as a good approximation to a conservative Hamiltonian system. We would now like to explore a framework which suggests that cellular automaton rules of the type just discussed might actually be realizable at the atomic scale. We don't have a specific practical proposal, but rather some general notions about the sort of physical systems which it might be profitable to explore.

Under the right conditions, atoms or molecules will arrange themselves in a regular lattice. For a bulk material, this lattice will be three-dimensional, while for material adsorbed on a convenient substrate, the lattice will be two-dimensional. Let us consider a two-layer (i.e., essentially two-dimensional) lattice of the type displayed in Fig. 17.

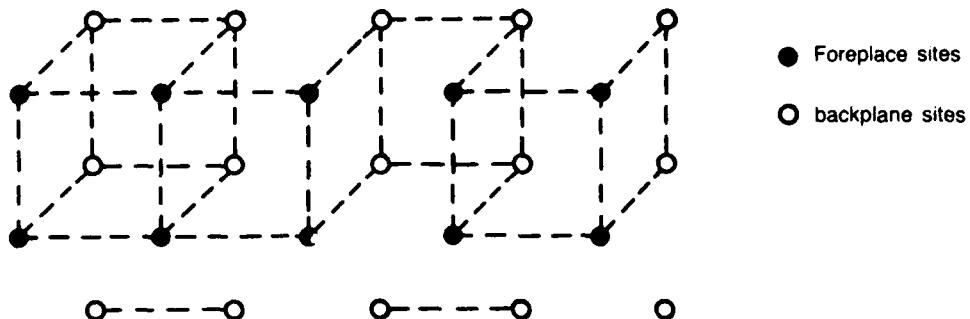


Figure 17

The lattice sites in the two layers (foreplane and backplane) are distinguished by open and filled circles. The basic idea is that the sites harbor some two-fold quantum mechanical degree of freedom (such as a spin, the presence or absence of an atomic excitation, etc.) which can be manipulated and used as a token for computing. For convenience, we will refer to this degree of freedom as a spin, although it need not actually be one.

There are interactions between "spins" at neighboring sites, and we have indicated the desired pattern of interactions by dashed and wavy lines. They will cause the "spins" on the sites to change with time and our goal is to cause this time evolution to occur in a way which carries out the cellular automaton rules discussed in the previous section. The simplest way to do this is to imagine that all the wavy line (dashed line) interactions can be turned on or off simultaneously from outside by some macroscopically

controllable agency such as a laser pulse. Suppose that the wavy line interactions can be turned on and then off in just such a way as to exchange spins between the foreplane and backplane sites (each wavy line connects just one foreplane and one backplane site).

Suppose further that the dashed line interactions, which connect up cells of four sites, either all in the foreplane or all in the backplane, can be turned on and then off in such a way as to effect the transformation on spins corresponding to the cellular automaton rules of the previous section. Then by alternately activating the dashed and wavy bonds, one would effect the cellular automaton rules as transformations on the "spins." Then by the discussion of all the previous systems, this microscopic device could be made to function as a reversible computer.

If we think of the site variables as really being elementary spins, it is easy to see what is involved in obtaining exchange. The most general interaction between two half integer quantum-mechanical spins $\vec{\sigma}_1$, and $\vec{\sigma}_2$ is

$$H_I = \alpha(t) \vec{\sigma}_1 \cdot \vec{\sigma}_2$$

The bond strength, α , depends on t , since we must imagine being able to manipulate from outside. If we turn this bond on and then off in such a way that

$$\int_0^\infty dt \alpha(t) = \pi$$

(a matter of properly tailoring the laser pulse, or whatever it actually is, that manipulates the bond) then it is easy to show that the net effect is simply to exchange the spin values (i.e., spin up or spin down) between the two sites. Although we have not done it explicitly, we believe it should be possible to construct a set of bonds for four spins which can be manipulated in such a way as to carry out the desired cellular automaton transformation.

If a scheme of the above type can be found, it suggests that a reversible atomic scale (and, therefore, one might hope, very fast) computer could be built. The obvious challenge is to find semi-realistic choices for sites, bonds, and the external driver of the bonds. We don't have any concrete response to this challenge but we think that materials questions of the kind raised here are a rather natural outcome of thinking about where reversible logic fits in the overall scheme of computing concerns. We have been struck by the extent to which previous work on reversible computing has focussed on abstract questions and would strongly recommend that future work begin to focus on physics questions. The framework we have presented is not necessarily the best one, but does give a way

of focussing on an interesting set of materials and physics questions, and might have the virtue of stimulating thought.

Quantum Mechanics Issues

The previous discussions have not made much of the fact that physics at the atomic scale is necessarily quantum mechanical. Indeed, the whole question of the role of quantum mechanical effects in small-scale computing devices has been only very sketchily explored in the literature.⁹ The scheme we have been discussing has one illuminating and bizarre quantum mechanical feature which we will explain, just to give an idea of the sort of issues involved.

The bonds of our lattice cellular automaton are alternatively switched on and off by some external system which acts as a clock and driver for the whole system. This driver is itself some mechanical system executing periodic motion. Let us for definiteness take it to be a rotator of some kind, rotating in some angular coordinate, θ , such that every time θ passes through some marker angle, θ_0 , the bonds responsible for switching spins on the lattice are briefly activated.

We can write down a fairly explicit Lagrangian for this system:

$$L = \frac{1}{2} I \dot{\theta}^2 + \left(\sum_{i=1}^N \sigma_1^{(i)} \cdot \sigma_2^{(i)} \right) \pi \dot{\theta} \delta(\theta - \theta_0) + \dots$$

The first term is just the rotator kinetic energy and says that, in the absence of other terms, the system just executes uniform rotational motion. The next term describes the interaction with the "wavy" bonds of the previous section: the spins are divided up into N pairs and the interaction of each pair with θ is such as to effect the exchange transition every time θ passes through θ_0 . The $\dot{\theta}$ factor ensures the same action on the spins no matter how fast θ is moving. The dots indicate the terms, not yet specified but similar in nature, responsible for the spin transformations on four spins at a time (needed to complete the cellular automaton rules).

In the classical approximation to the motion of θ , the rotator proceeds at constant velocity and one cellular automaton transformation is executed per cycle. The quantum-mechanical version of the motion of θ is somewhat different. The rotator interacts with the computer coordinates through the sum $\sum \sigma_1^{(i)} \sigma_2^{(i)} + \dots$, and, as the calculation proceeds, this sum

takes on an essentially random sequence of values. This is roughly equivalent to saying that θ is moving in a one-dimensional random potential.

In a random potential, there are no propagating states, and all wave functions decay exponentially with distance. If a computation takes N steps, we prepare the system in a state localized around $\theta = 0$ and the computation is completed when θ is finally observed at $2\pi N$. The exponential decay of wave functions probably means that the time to complete long calculations increases exponentially with N ! To know under what circumstances this would be a practical problem, we would have to have a much more concrete model to work with. This observation could be elaborated further, but is meant to give an example of the peculiar phenomena that must be understood when we try to think about computing at the quantum mechanical level.

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